

Feedback in Clusters

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Feedback in Clusters

- Evidence for AGN Feedback in clusters
- Large scale, metal-enriched outflows
- Cavity Dynamics, turbulence; IXO: good prospects
- AGN fueling, feedback mechanism

MS0735.6+7421

$\sim 10^{62}$ erg
1/4 keV/Baryon

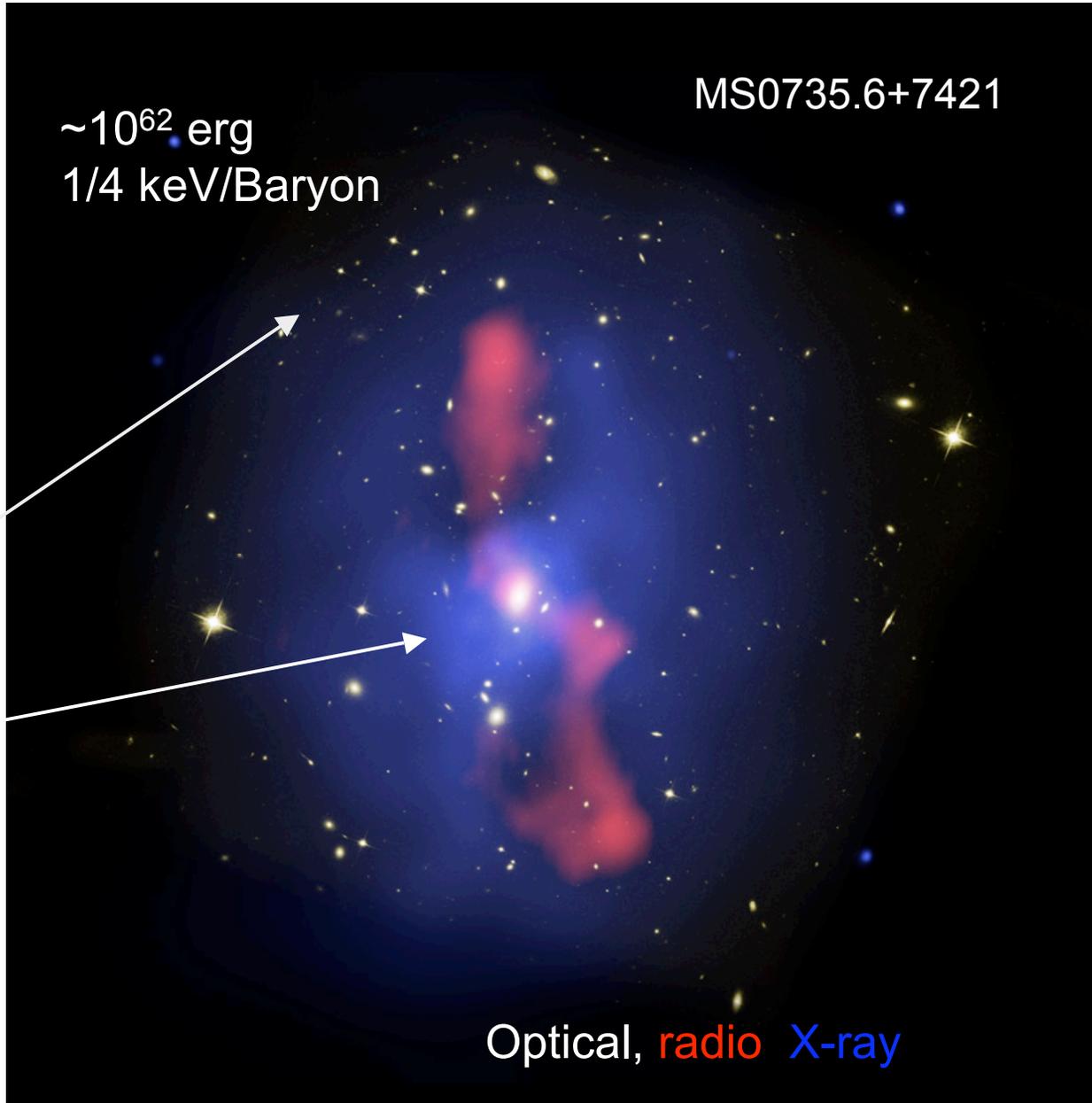
hot

cool

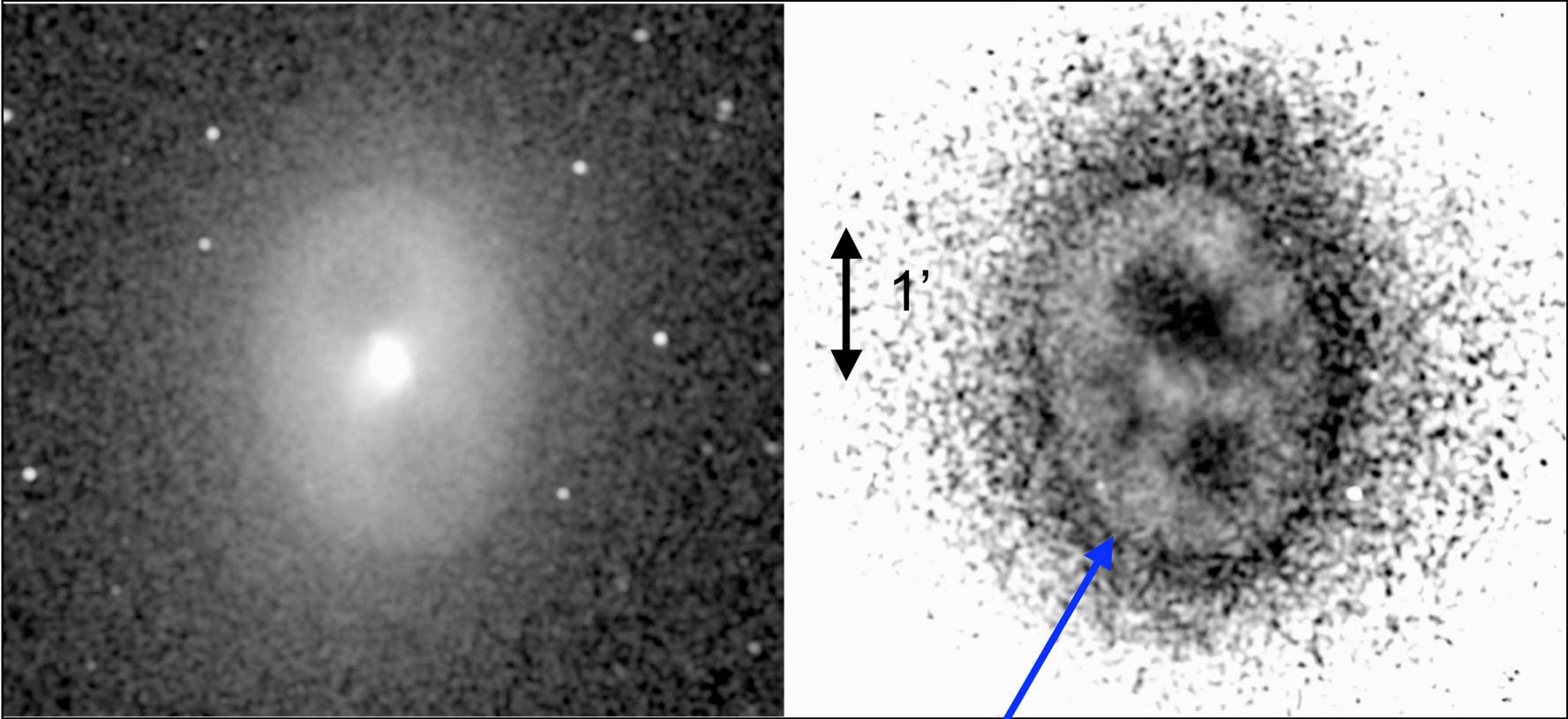
200 kpc

Optical, radio X-ray

McN + 05, 09



Chandra LP 500 ksec Image of MS0735.6+7421

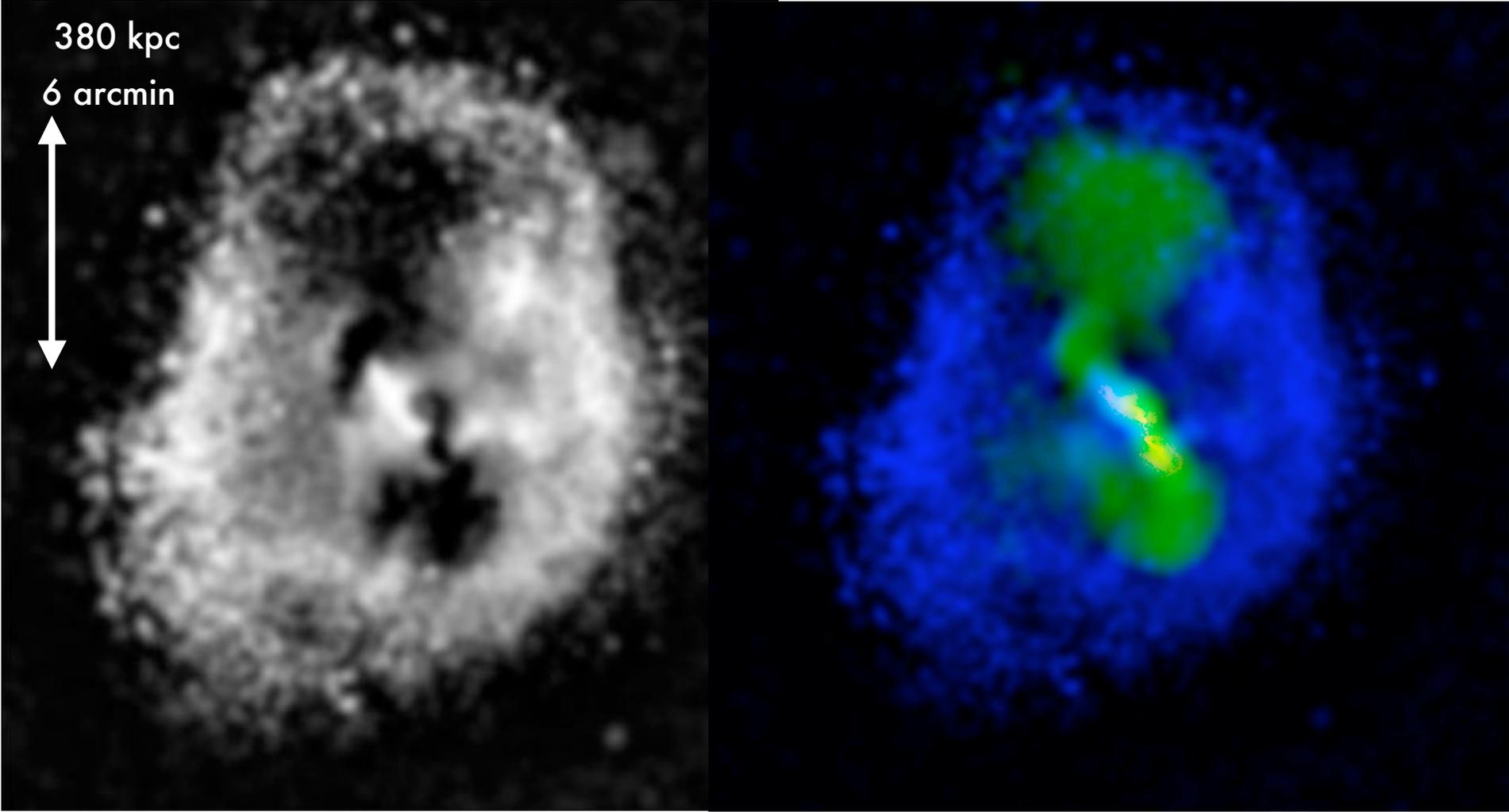


Shock front

McN, Wise + 10

10^{61} erg

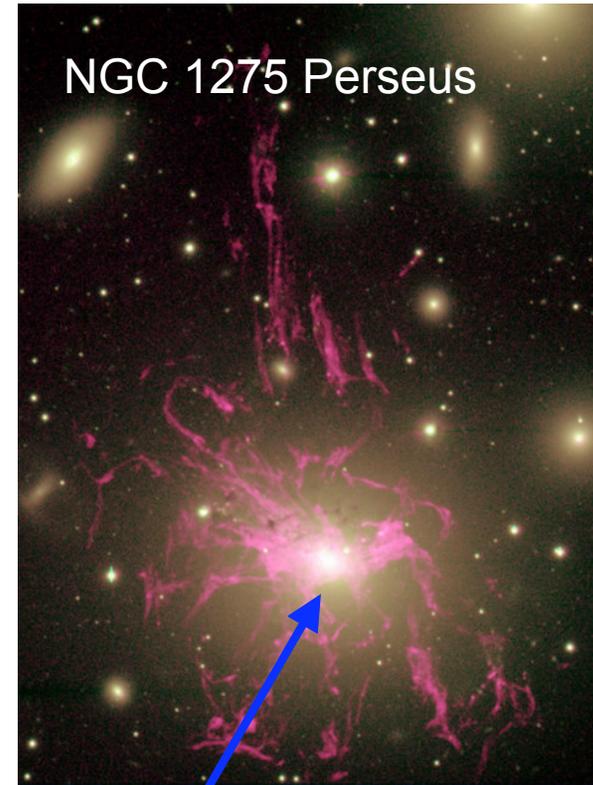
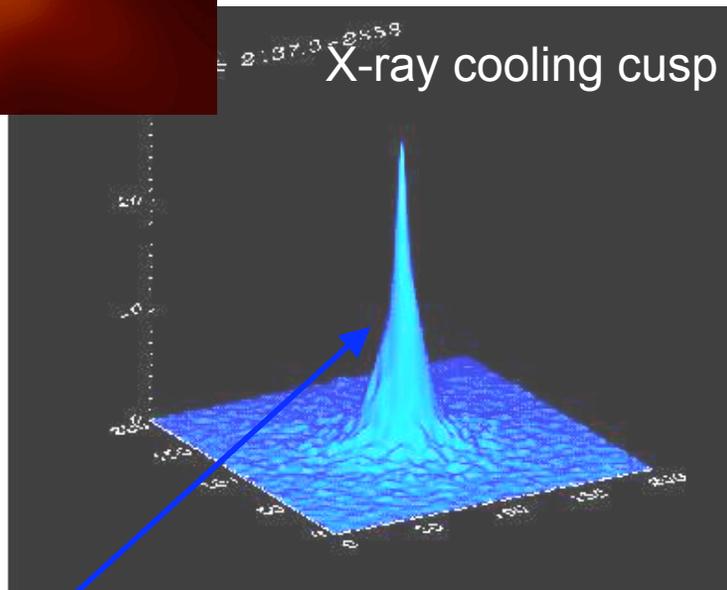
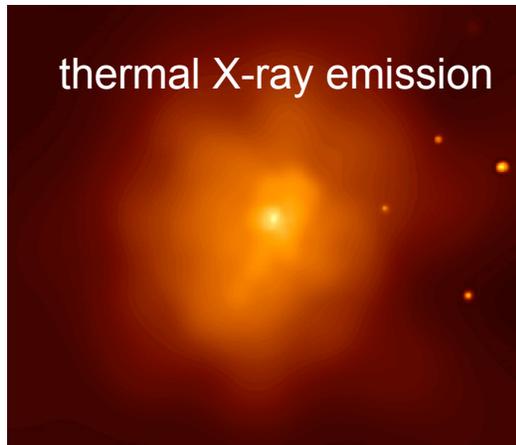
Hydra A



Wise + 07
Nulsen + 05
McN + 00

320 MHz + 8 GHz

Cooling Flows



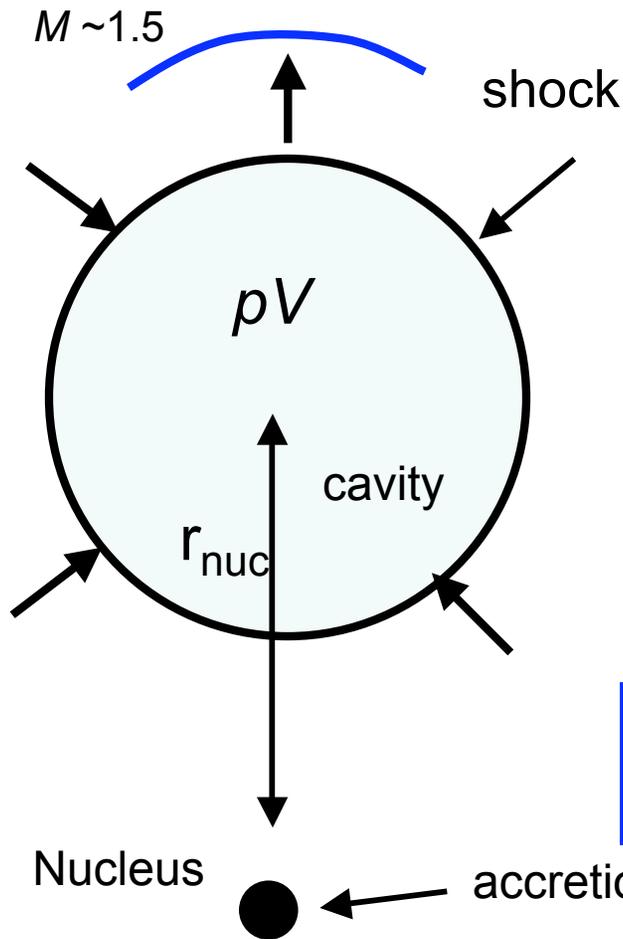
X-ray power 10^{44-45} erg s⁻¹ exceeds radio synchrotron power 10^{40-42} erg s⁻¹

- implies cooling flow: $n_e \sim 10^{-1}$ cm⁻³ $\dot{M} = 10-1000$ Mo yr⁻¹
- cooling flow problem: star formation $\sim 1\%$ \dot{M}

XMM: cooling rate $\ll M_{gas}/t_{cool}$

Peterson + 01

Measuring Jet Power with X-ray Cavity Dynamics



- energy & age measured directly
- measure mechanical (not synchrotron) power

1) cavity

$$E_{cav} = \frac{\gamma p V}{\gamma - 1} = 2.5 p V - 4 p V \quad t_{cav} = r_{nuc} / v_{buoy}$$

2) shock

$$E_{shock} \approx \Delta p V \quad t_{shock} \approx r_{shock} / c_s$$

$$E_{tot} = E_{cav} + E_{shock} + (E_{photon}) = 10^{55} - 10^{62} \text{ erg}$$

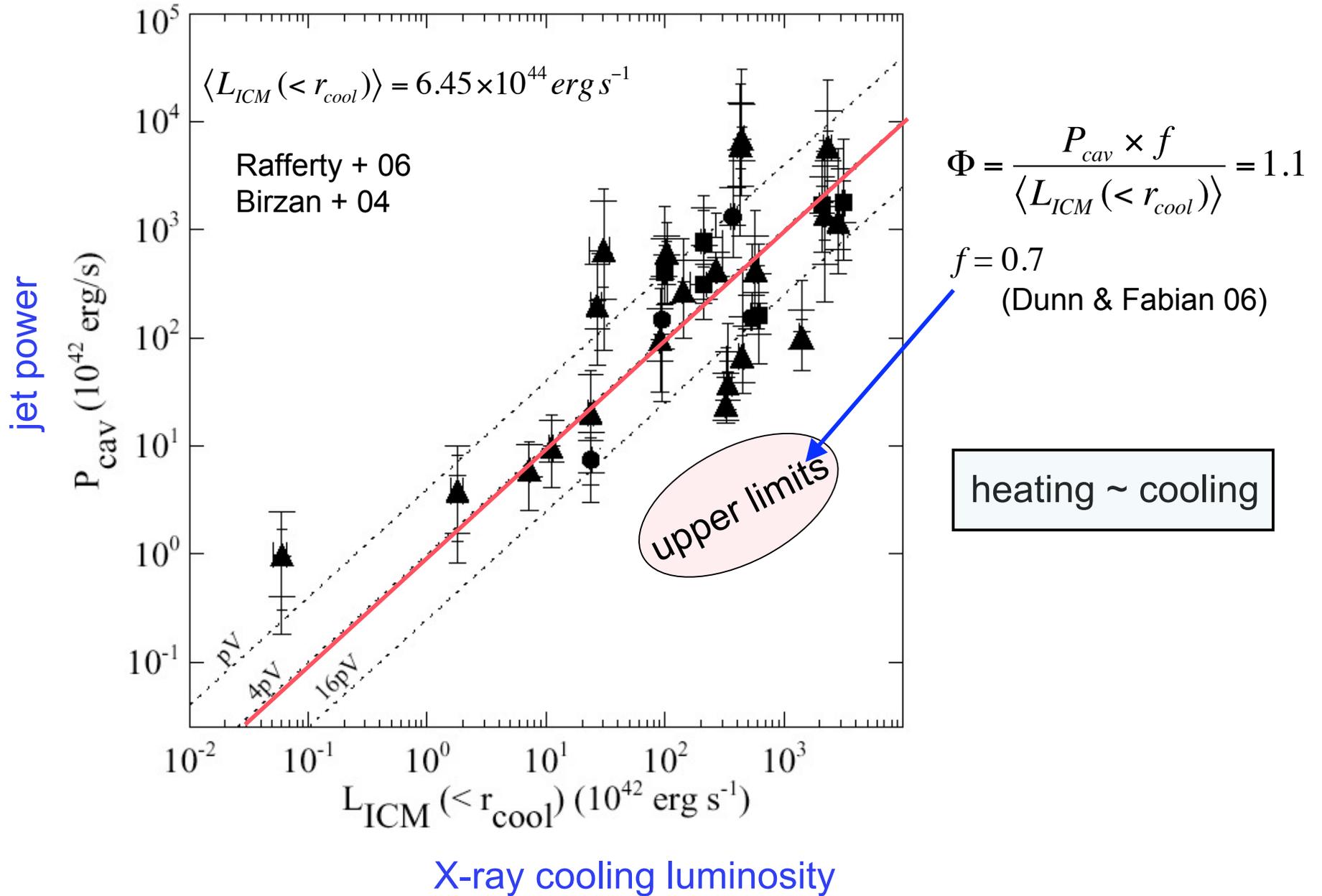
McNamara + 00,01; Birzan + 04

Theory: Ruszkowski, Heinz, Bruggen, Begelman, Voit, Churazov, T. Jones, etc.

slow gas motions $< c_s$, gentle heating
IXO will test this

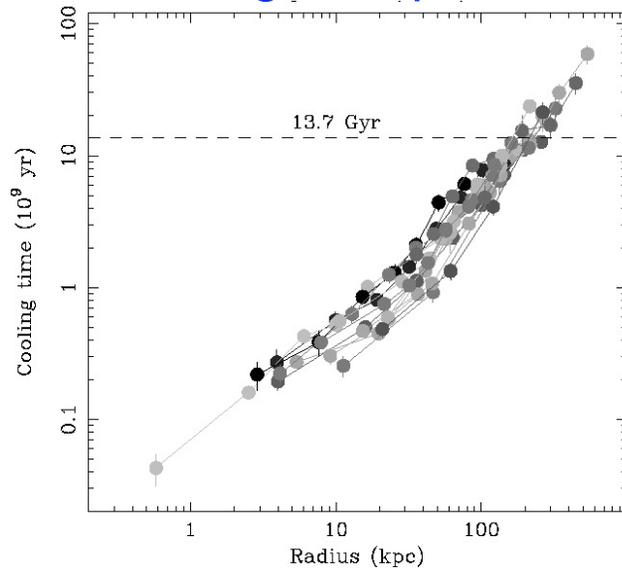
X-ray Evidence for Feedback

Heating & Cooling Diagram: CFs Quenched



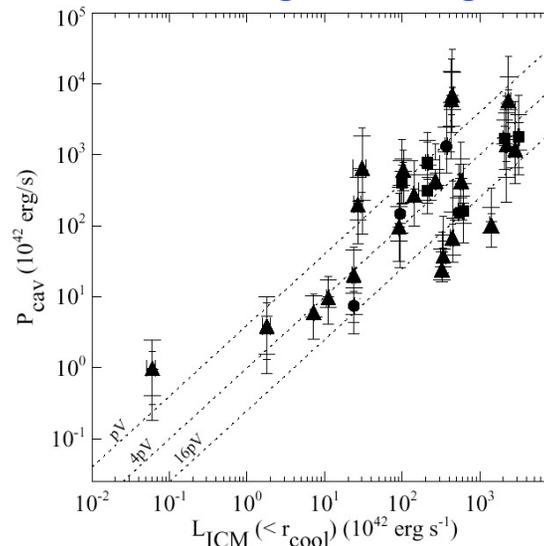
Conditions for AGN-Regulated Feedback Loop

cooling time profiles



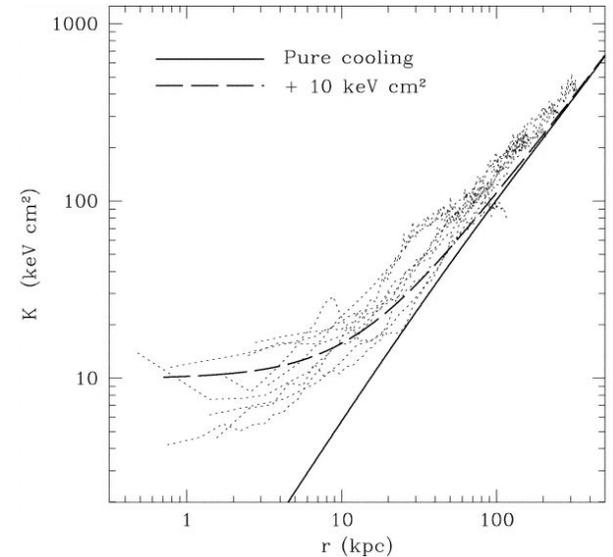
Voigt & Fabian 04

heating/cooling



Rafferty et al. 06
Birzan et al. 04

entropy profiles



Voit & Donahue 05
Donahue et al. 06
Voit 05

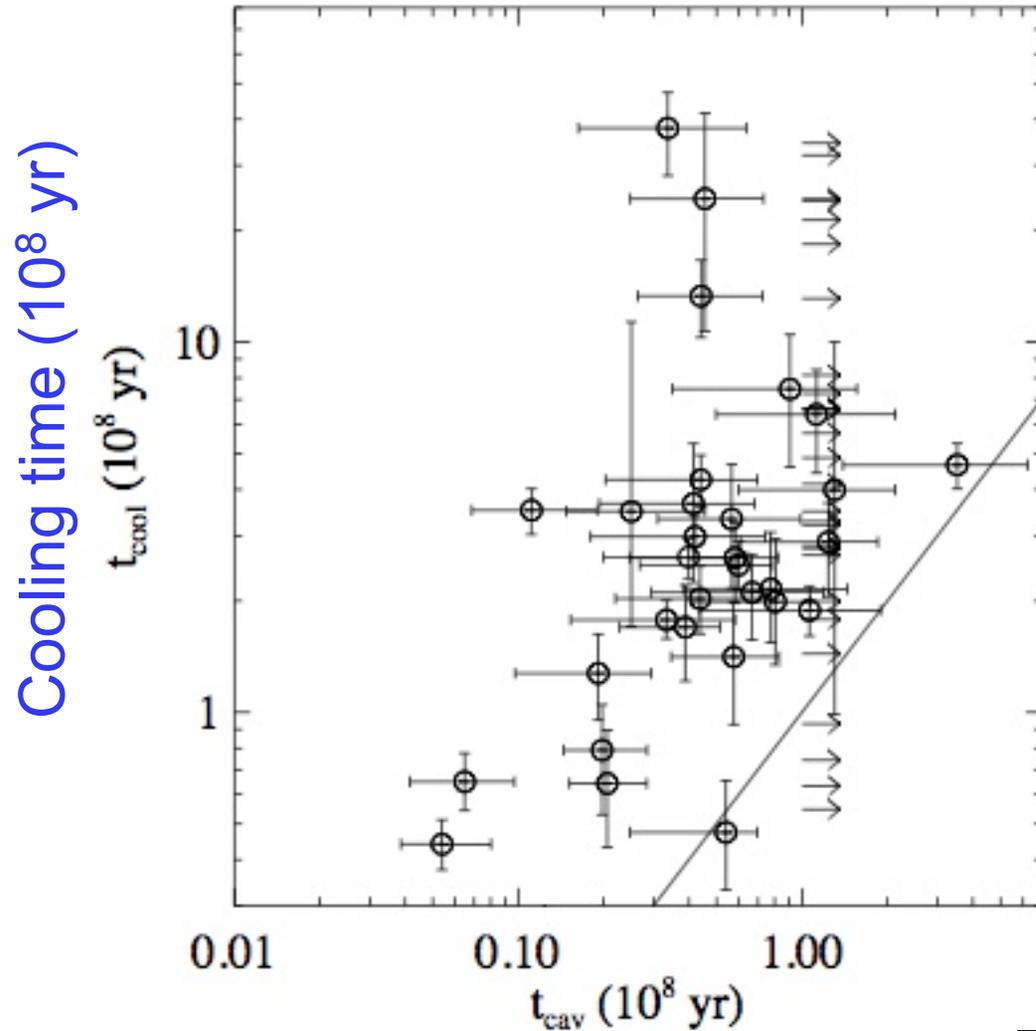
1) $t_{\text{cool}} \sim t_{\text{cav}} \sim 10^8 \text{ yr}$

2) $L_{\text{AGN}} \sim L_x$

3) Entropy floors

See Voit & Donahue 05, Peterson & Fabian 06, McNamara & Nulsen 07 ARAA

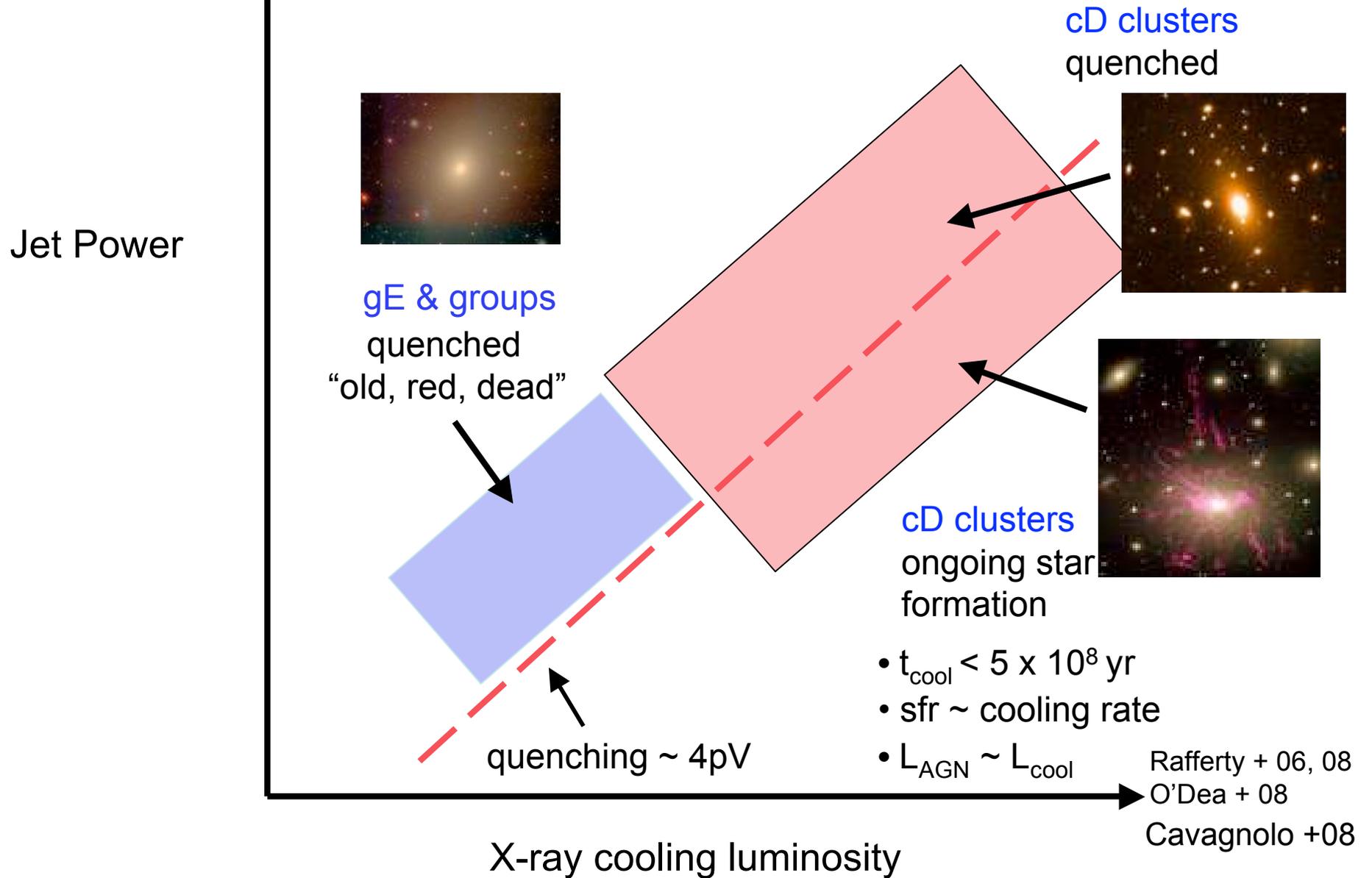
Cooling time \geq cavity buoyancy ages



Cavity age (10^8 yr)

Rafferty + 08

“Radio Mode” Feedback



AGN Feedback Regulates Cooling & Star Formation

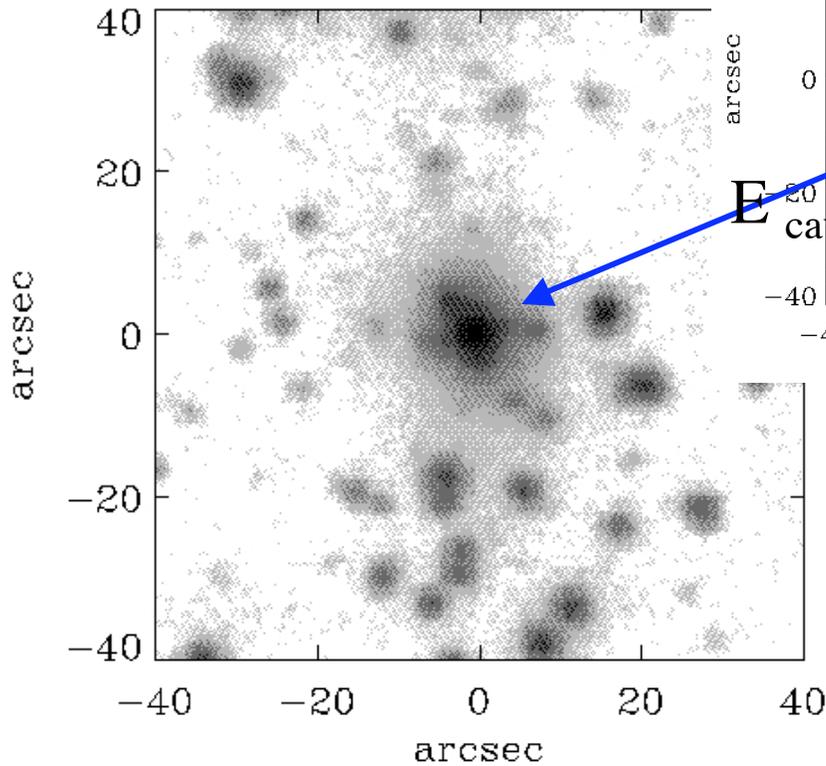
IXO Will test this framework through
measurements of

ICM Cooling, turbulence, & cavity dynamics

Star formation rate consistent with net cooling rate

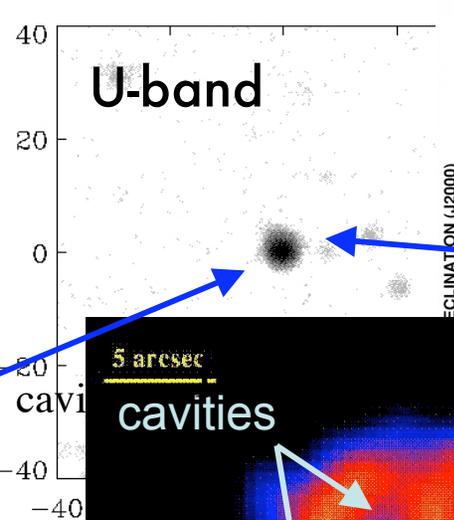
Abell 1835

R-band

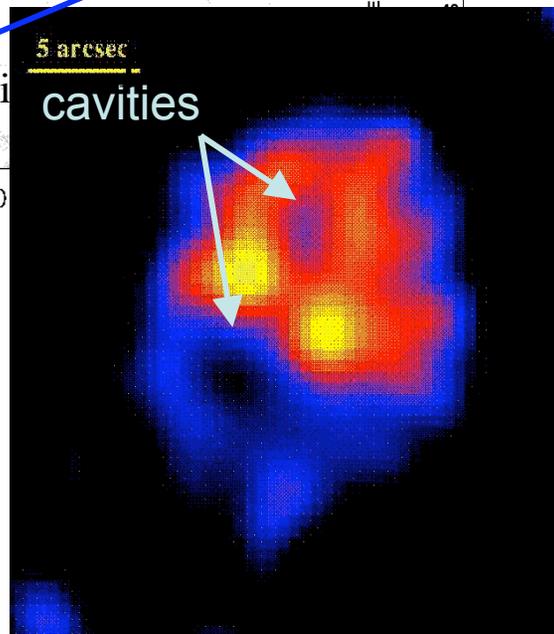
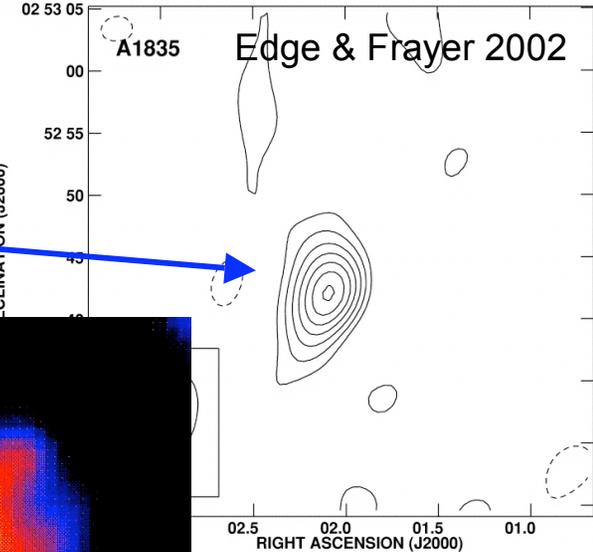


Starburst

U-band



10^{11} Mo of Gas



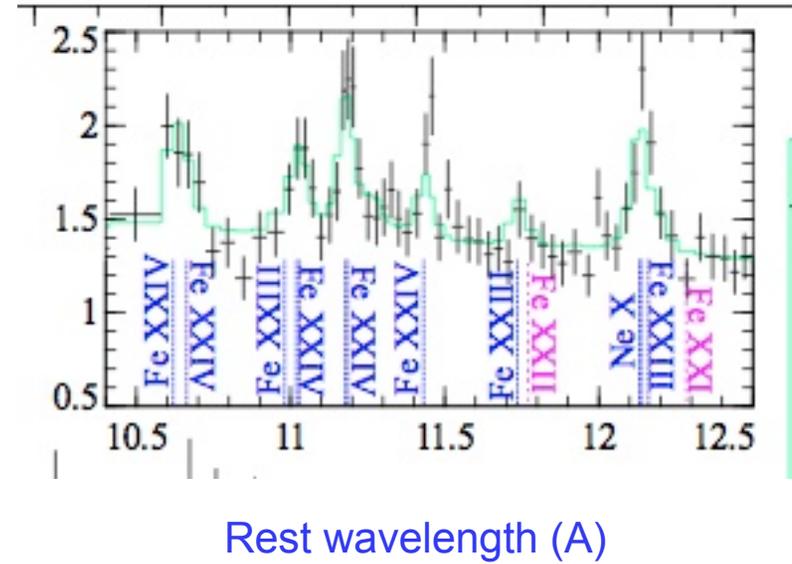
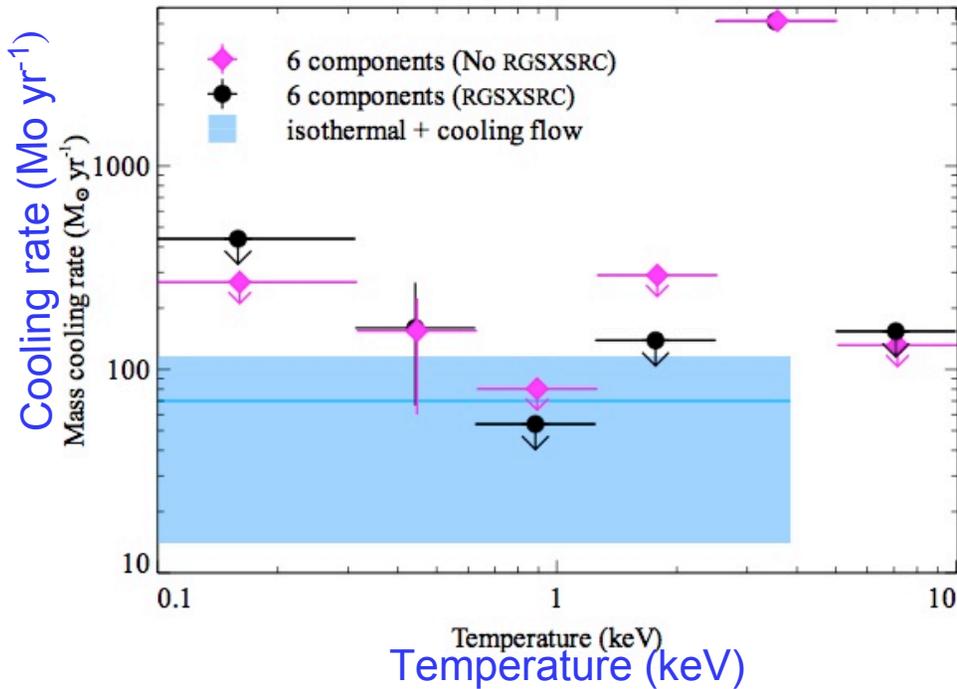
$$\text{SFR} = 100 - 200 \text{ Mo yr}^{-1} = L_{x,\text{spec}}$$

McNamara et al. 06

$$E_{\text{cavity}} = 1.7 \times 10^{60} \text{ erg}$$

$$P_{\text{cavity}} = 1.4 \times 10^{45} \text{ erg s}^{-1} \sim L_{x,\text{cool}}$$

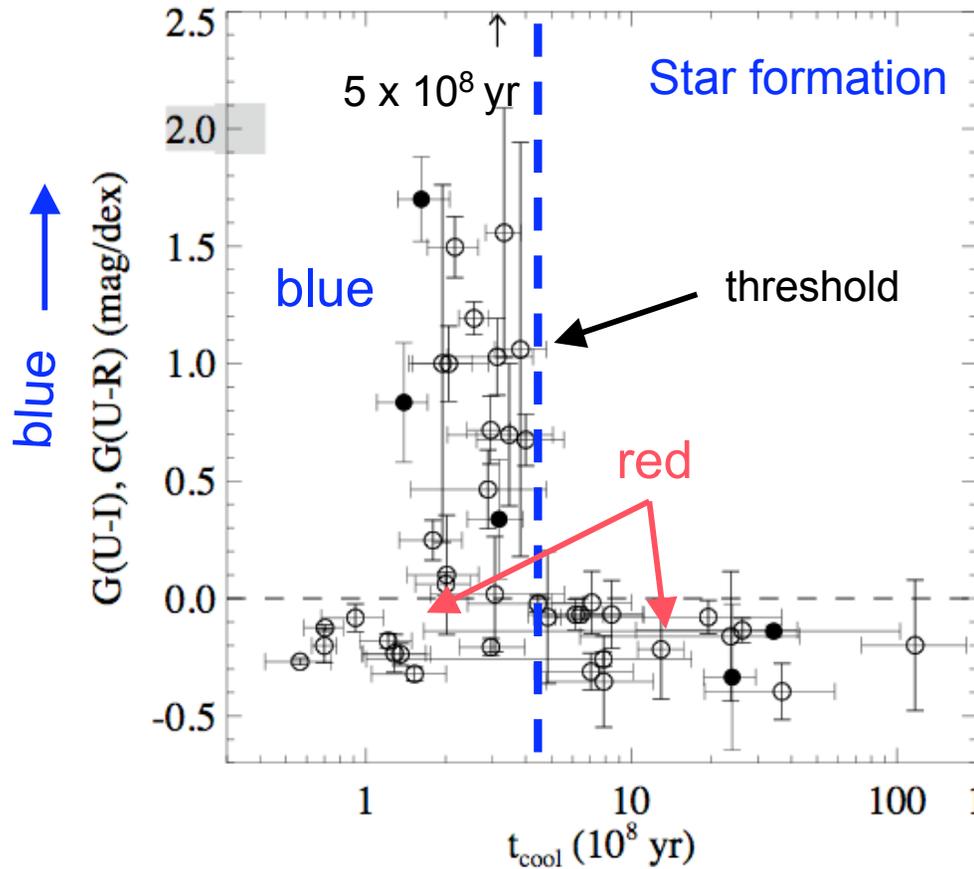
Cooling in Abell 1835



SFR = 100-200 $M_{\odot} \text{ yr}^{-1}$ (McN+ 06)

Cooling rate = 70-140 $M_{\odot} \text{ yr}^{-1}$

star formation threshold: $t_{\text{cool}} \sim 500 \text{ Myr}$



Rafferty + 08

X-ray cooling time

Cavagnolo + 08 Ha threshold
Voit + 09

- Cool gas & Star formation linked to cooling, X-ray atmospheres

Thermal conduction, thermal instability? IXO

Metal-Enriched Outflows: New Territory for IXO

IXO Reference Specs

Angular resolution: 5" HPD @ 7 keV

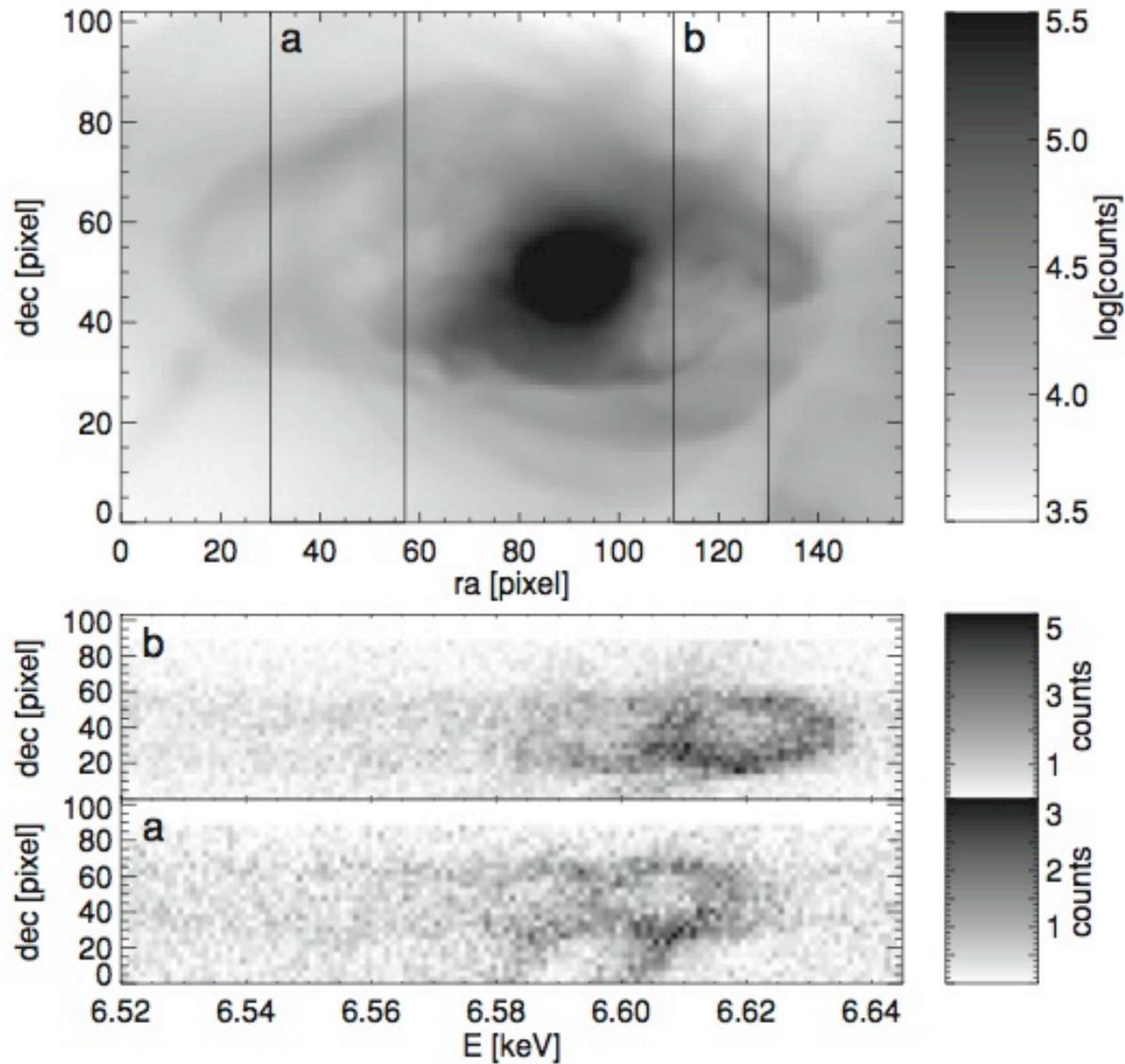
Spectral resolution: 2.5 eV up to 7 keV $\sim 125 \text{ km s}^{-1}$

Effective area: 6000 cm² @ 6 keV (25 X Chandra)

Flash AMR code for gas hydrodynamics embedded
in 10^{15} Mo halo simulated in Gadget (Springel +01)

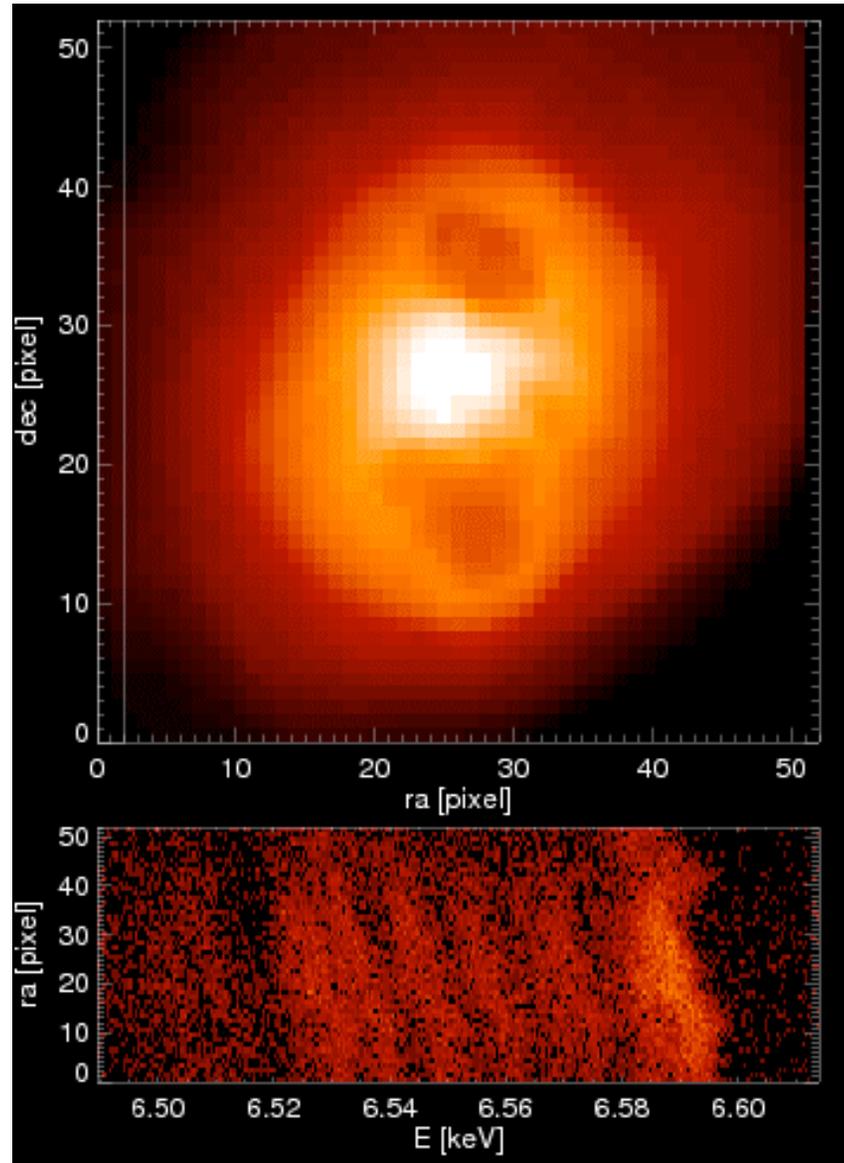
Heinz + 10

IXO Calorimeter Spectroscopy of Cavities



Virtual 250 ks IXO spectrum of Hydra A -- Heinz + 10

Video of Fe line shifts in Perseus



Heinz, Bruggen, Barsony 10

What can we learn?

Model: $V_{\text{exp}} \pm 350 \text{ km s}^{-1}$

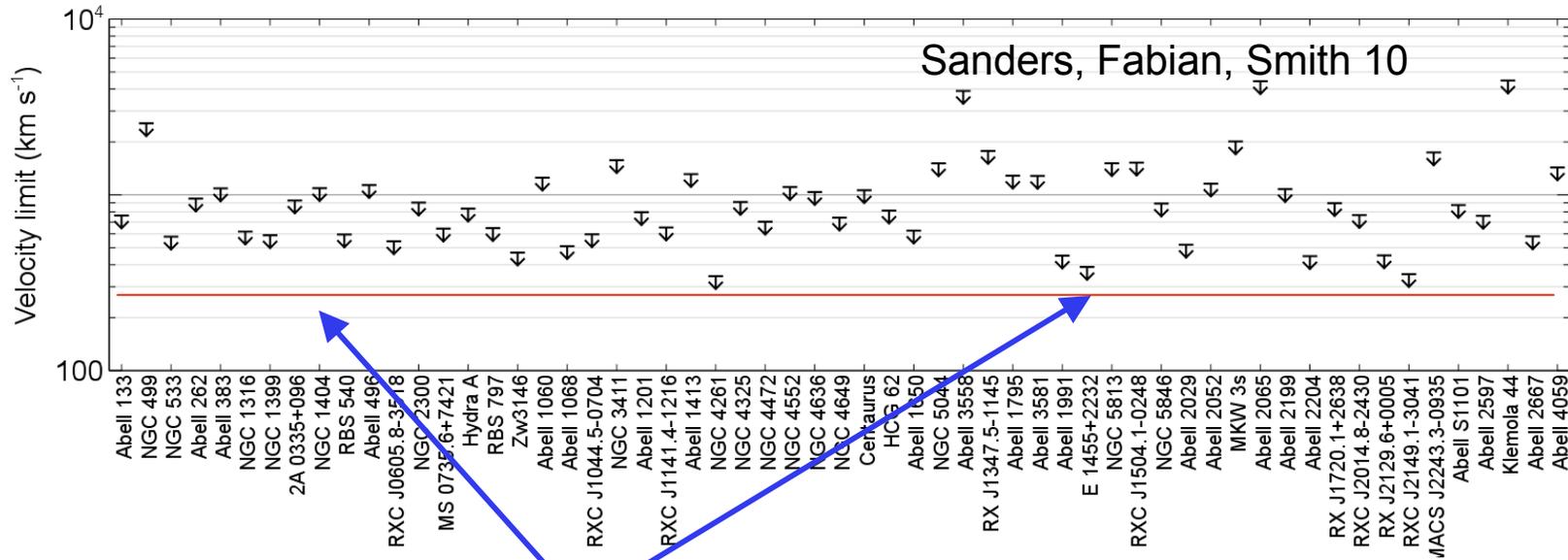
Cavity orientation: from velocity centroids of cavities

Emission measure maps: multiphase gas, local heating maps, temperature, entropy, etc.

Expansion dynamics: **limited by turbulence** to powerful AGN

Sensitivity to cavity expansion limited by turbulence

A1835: $v_{\text{turb}} < 274 \text{ km s}^{-1}$, $r < 30 \text{ kpc}$ (Sanders + 10)



$V_{\text{turb}} < \text{few hundred km s}^{-1}$

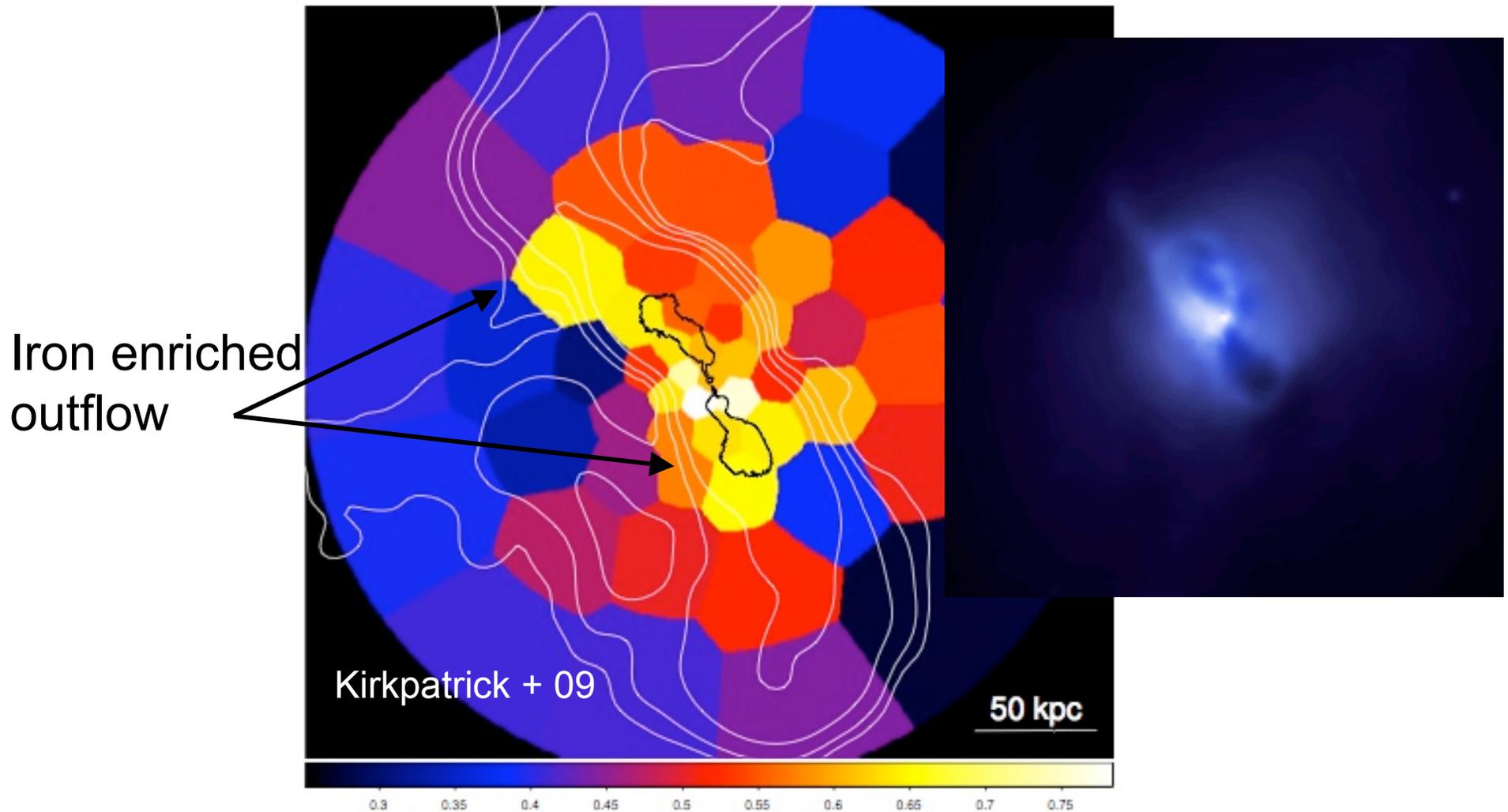
Expansion detectable for $v_{\text{exp}} > v_{\text{turb}}$

Powerful AGN will be measurable

$$v_{\text{los}} \propto \left(\frac{P_{\text{jet}}}{\rho_{\text{ICM}}} \right)^{1/3}$$

Heinz + 10

Hydra A Metal Enriched Outflow



$$\Delta M_{Fe} = 2 - 7 \times 10^7 M_{\odot}$$

R ~ 120 kpc

AGN-Jets disperse metals throughout ICM

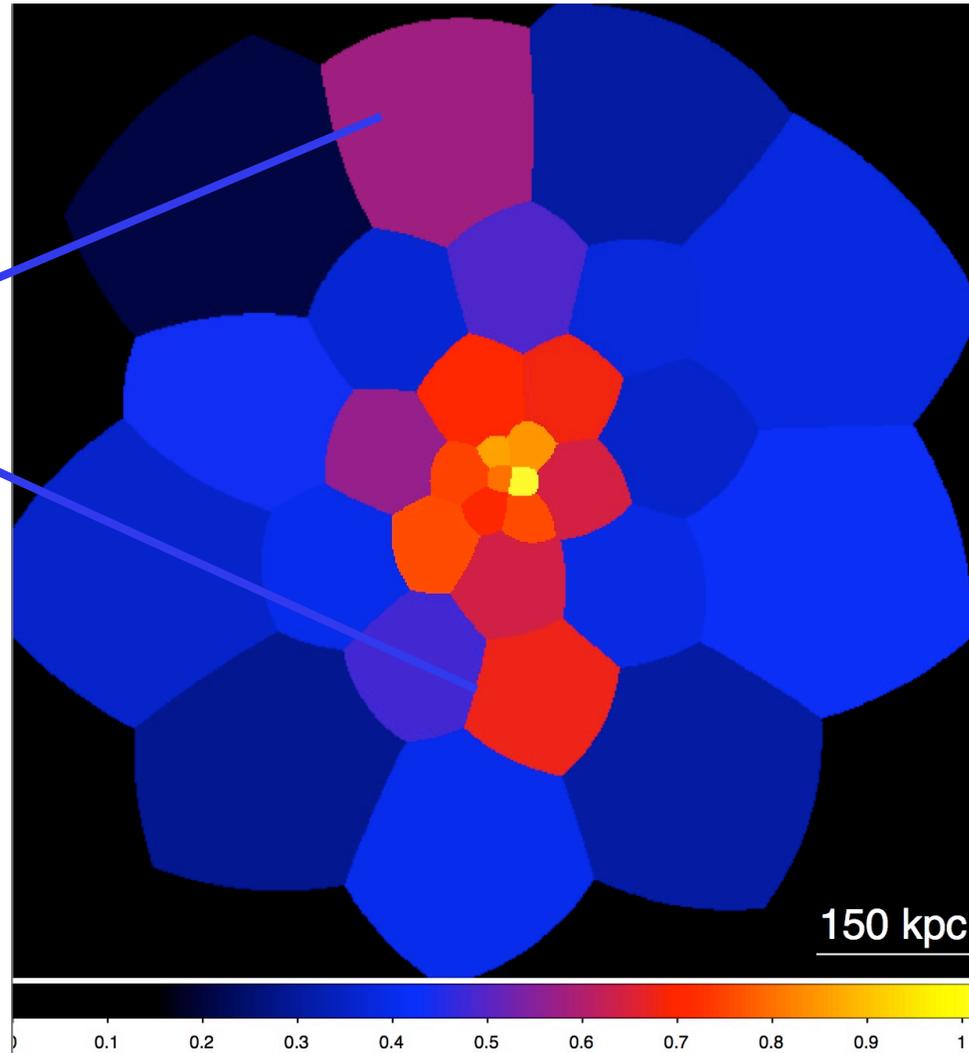
See also Simionescu, Werner + 08, 09

MS0735 Metal-Enriched Outflow

500 ks Chandra LP

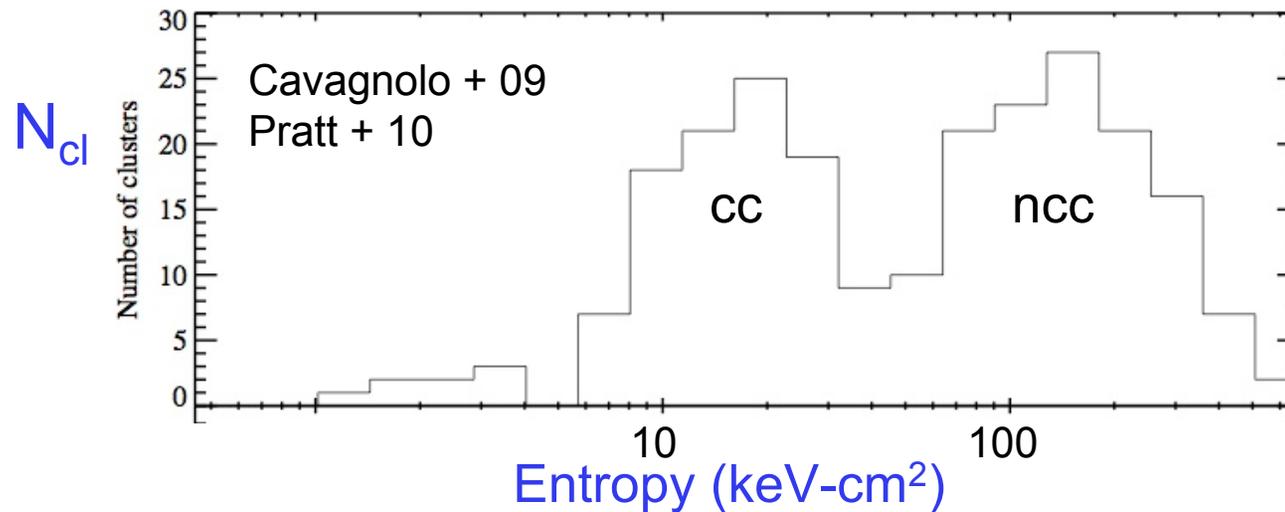
McN+10

outflow



IXO: iron line traces cool, metal-enriched gas entrained by radio jets

Cluster Turbulence: Affects heat transport properties of hot gas



Modest turbulence $\sim 100 \text{ km s}^{-1}$ = tangled fields, no HBI,
no cooling flows

Low turbulence $< 100 \text{ km s}^{-1}$ = HBI = tangential fields, no
heat conduction to core, cooling flow forms

Parrish + 10, Ruszkowski & Oh + 10

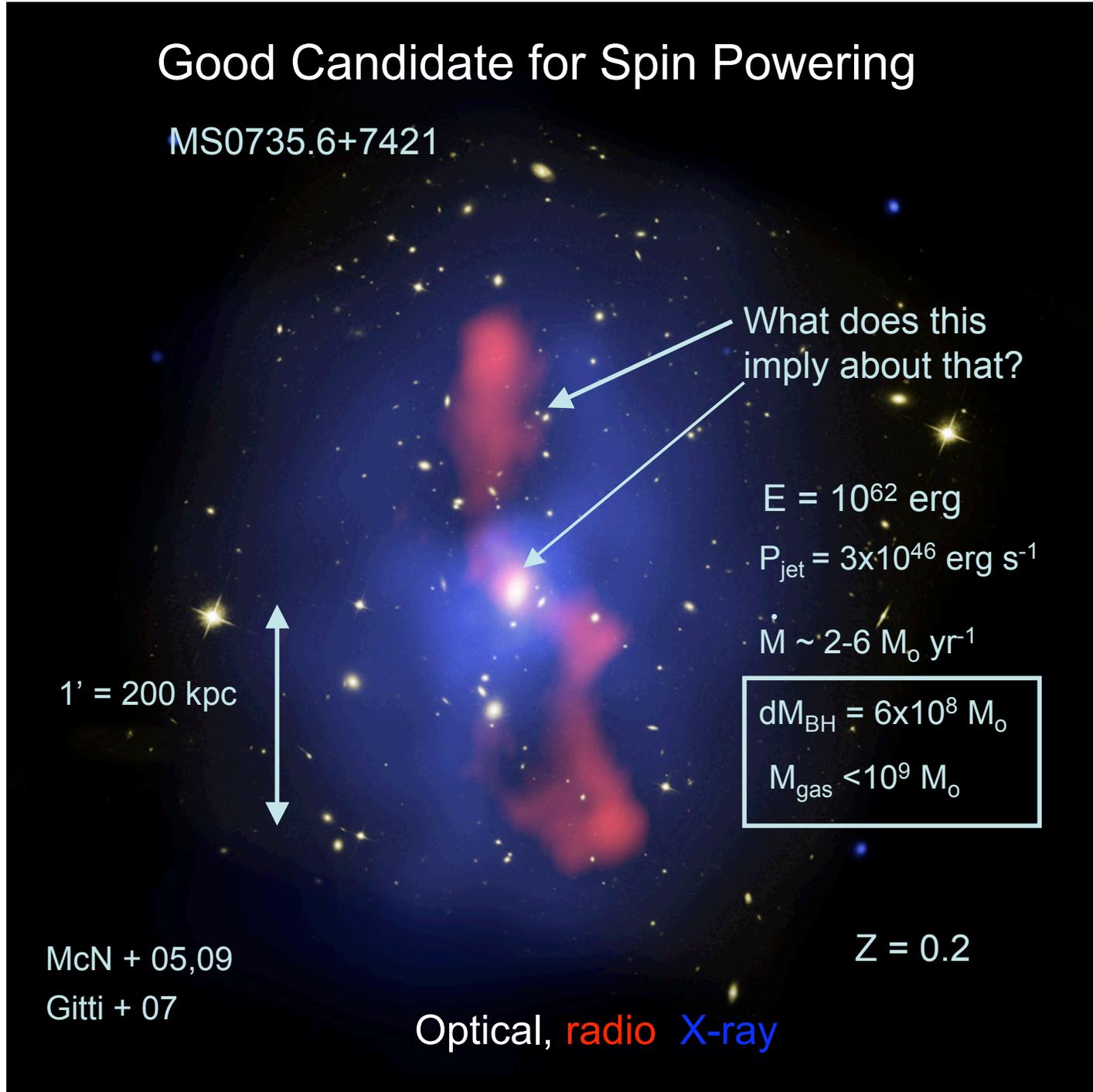
Ratio of turbulent pressure to thermal pressure $\sim 10\%$

How are AGN Fueled?

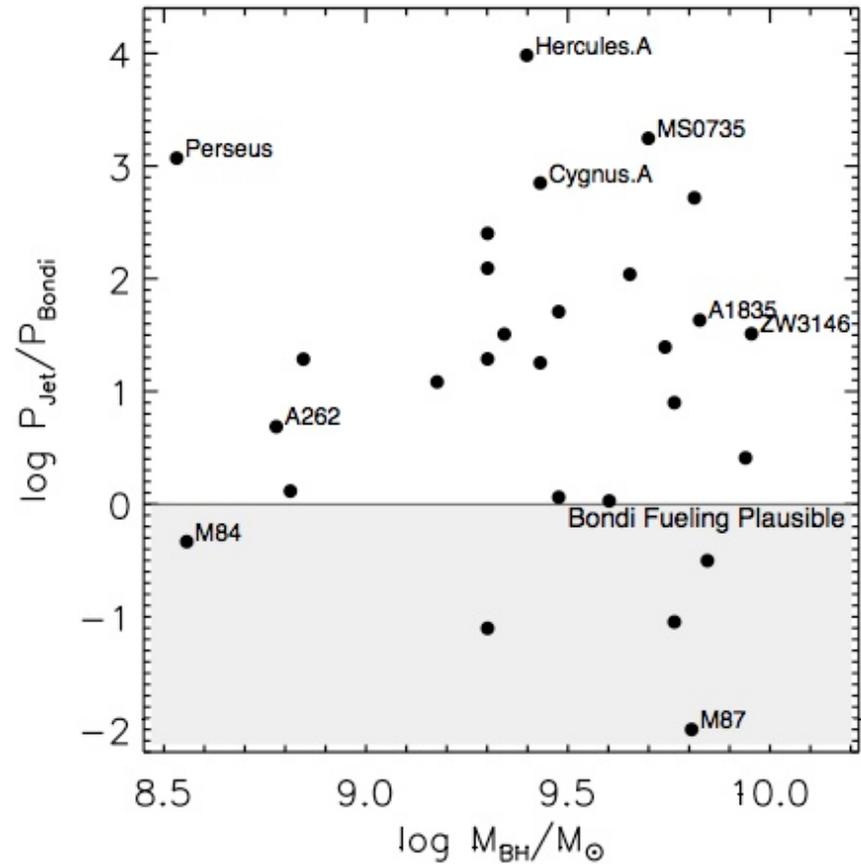
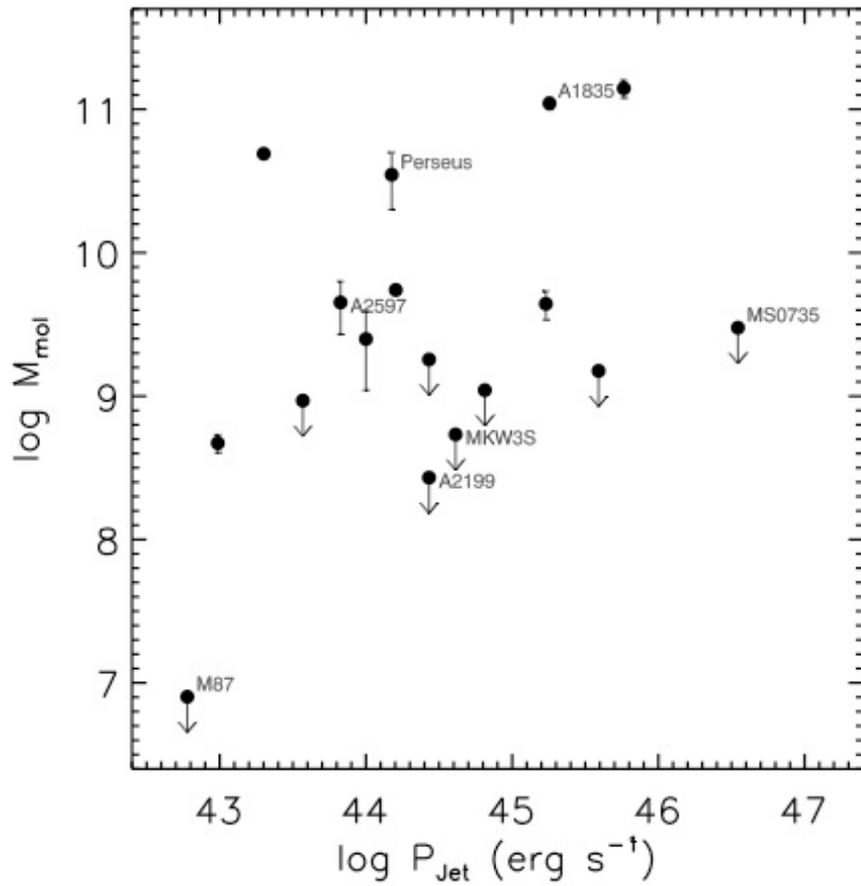
Central question for feedback

Good Candidate for Spin Powering

MS0735.6+7421



How are AGN Fueled and Powered?



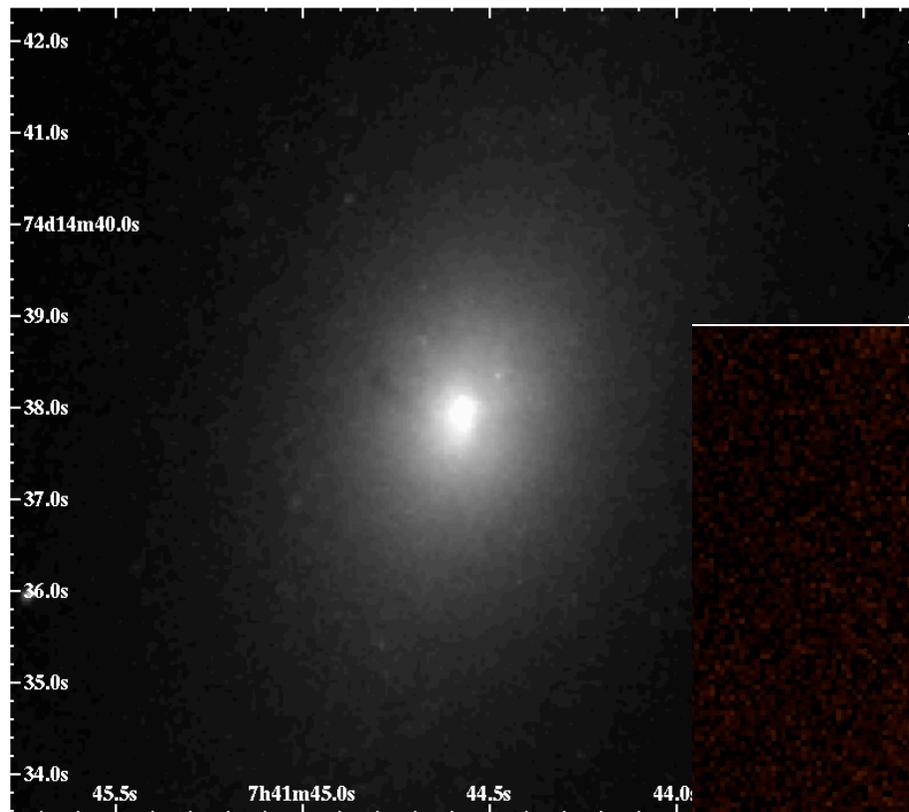
Bondi accretion won't work without UMBHs

Spin?

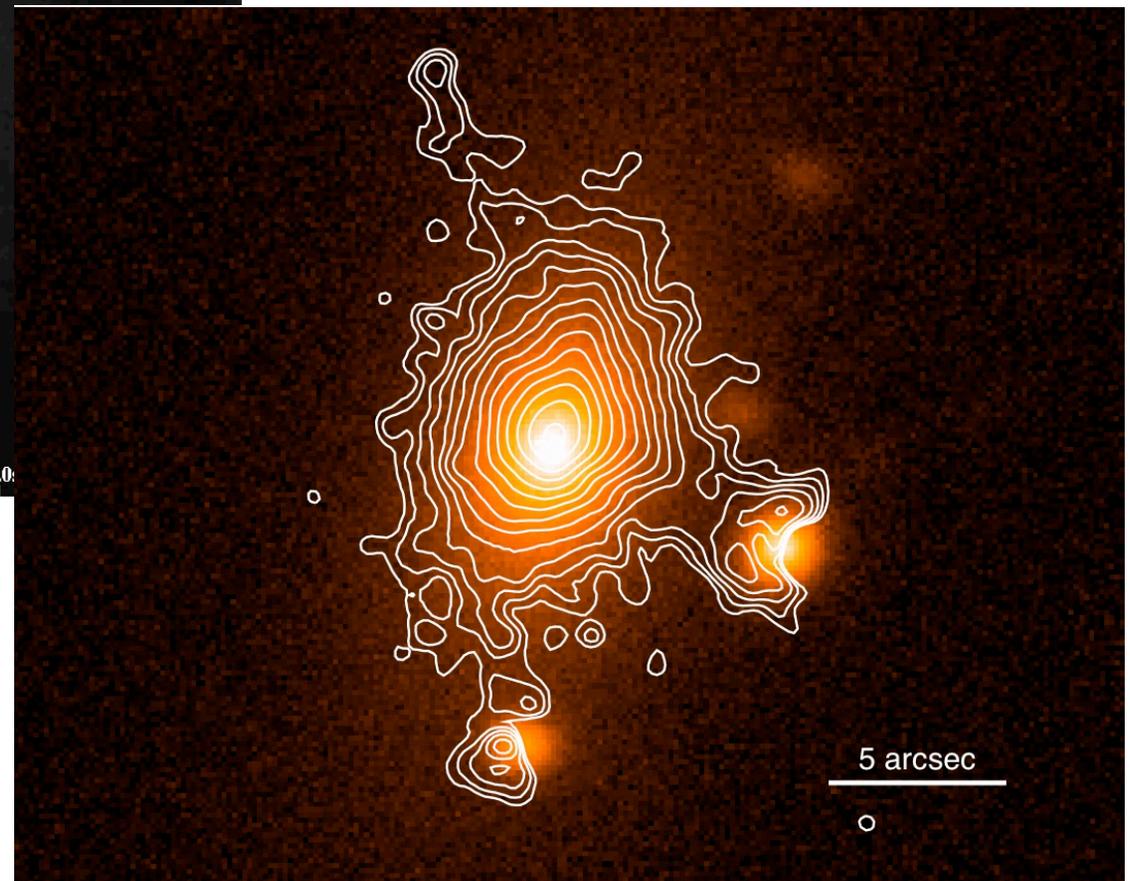
McN + 10

MS0735 $z=0.216$

HST I-band



WIYN R-band + H α



Conclusions

AGN Feedback:

- IXO: jet dynamics & heating of ICM
- Measure velocities of metal-enriched outflows
- Locate regions where gas is heated
- Test cooling, star formation, feedback
- Turbulence & transport properties of ICM